Grain yield and population densities of new corn hybrids released by the INIFAP and UNAM for the High Valleys of Mexico*
Rendimiento de grano y densidades de población de nuevos híbridos de maíz liberados por el INIFAP y UNAM para los Valles Altos de México*

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SUMMARY

In Mexico, corn (*Zea mays* L.) is one of the most important cereals from the alimentary, industrial, social, political, and cultural points of view. It is grown in different agroecological niches, water regimes, and management systems. The objective of the present research work was to study the optimum plant density per area unit and its effect on grain yield and agronomical characteristics of different corn hybrids. Six corn hybrids (H-51 AE, H 53 AE, H 47 AE, H 49 AE, Tsíri PUMA, and H-48) and three plant densities (50 000, 65 000, and 80 000 plants ha^{-1}) were evaluated. Sowing was done during the spring-summer season, 2015, in field owned by the FESC-UNAM and CEVAMEX-INIFAP. A completely randomized block design was used with four replicates. Significant differences ($P \leq 0.05$) were detected for genotypes (G) in the variables of grain yield, plant height, ear height, days to male and female flowering, volumetric weight, grain weight, ear length, and grains per ear. Moreover, the effect of the environment (E) was significant ($P \leq 0.05$) for the same variables, with the exception of ear length. No significant differences ($P \geq 0.05$) were registered for the densities factor (D). Only the G×E interaction had significant differences ($P \leq 0.05$) in the grain yield trait. The better environment was CEVAMEX, with a mean yield of 5497 kg ha^{-1}. The Tsíri PUMA hybrid had the best grain yield with 5856 kg ha^{-1}. Although there were no differences for the studied interactions, the 65 000 plants ha^{-1} population density was the most appropriate. The densities factor did not affect the performance of the evaluated hybrids. Therefore, we recommend using 65 000 plants ha^{-1} to avoid investing in large amounts of seeds.

Index words: *hybrids, male sterility, population densities,* Zea mays L.

RESUMEN

En México, el maíz (*Zea mays* L.) es uno de los cereales más importantes desde el punto de vista alimenticio, industrial, social, político y cultural. Su

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siembra se realiza bajo diferentes nichos agroecológicos, regímenes de humedad y sistemas de manejo. El objetivo del presente trabajo de investigación fue estudiar la óptima densidad de planta por unidad de superficie y su efecto sobre el rendimiento de grano y características agronómicas de diferentes híbridos de maíz. Se evaluaron seis híbridos de maíz (H-51 AE, H-53 AE, H-47 AE, H-49 AE, Tsíri PUMA y H-48) y tres densidades de planta (50 000, 65 000 y 80 000 plantas ha^{-1}). La siembra se realizó durante el ciclo primavera verano 2015, en terrenos de la FESC-UNAM y CEVAMEX-INIFAP. Se utilizó un diseño de bloques completamente al azar con cuatro repeticiones. Se detectaron diferencias significativas ($P \leq 0.05$) para genotipos (G) en las variables rendimiento de grano, altura de la planta, altura de la mazorca, días a floración masculina y femenina, peso volumétrico, peso de grano, longitud de mazorca y granos por mazorca. Asimismo, el efecto del ambiente (A) fue significativo ($P \leq 0.05$) para estas mismas variables, excepto para longitud de mazorca. No se registraron diferencias significativas ($P \geq 0.05$) para el factor densidades. Solo la interacción G×A, detectó diferencias significativas ($P \leq 0.05$) en la variable rendimiento de grano. El mejor ambiente fue CEVAMEX, con un rendimiento promedio de 5497 kg ha^{-1}. El híbrido Tsíri PUMA, obtuvo el mayor rendimiento de grano con 5856 kg ha^{-1}. Aunque no se encontraron diferencias para las interacciones estudiadas, la densidad de población con 65 000 plantas ha^{-1} fue el más apropiado. El factor densidades no afectó el desempeño de los híbridos evaluados. Por lo tanto, se recomienda usar 65 000 plantas ha^{-1}, para evitar que el agricultor invierta en la compra de grandes cantidades de semillas.

Palabras clave: *híbridos, androesterilidad, densidades de población,* Zea mays L.

INTRODUCTION

Corn (*Zea mays* L.) is one of the most important crops in several regions of the world. Depending on the production region, the type of corn and the purpose production varies greatly. In 2018, approximately 193 million ha were sown with corn, with a grain yield of 5923 kg ha^{-1}; about 80% is cultivated under rainfed conditions and the rest with irrigation (FAOSTAT, 2020). In Mexico, around 15 million tons of corn are imported (SIAP, 2018), making it urgent to increase production and to have varieties with greater productivity. In 2018, around 7567 million ha were sown with a mean yield of 3759 kg ha^{-1}, and a production volume of 26 582 million tons. The mean yield obtained is generally low, compared with other countries; this is because of among other factors, biotic and abiotic stresses that commonly limit production (Virgen-Vargas *et al*., 2016; Tadeo-Robledo *et al*., 2017).

In the High Valleys of the Central Mesa of Mexico, which include the states of: Puebla, Hidalgo, Tlaxcala, Querétaro, Michoacán, Morelos, State of Mexico, and Mexico City, at an altitude above 2200 meters above sea level (masl), about 1.5 million ha are cultivated with corn. In these areas, the prevailing production systems are with residual humidity, point irrigation, and good rainfall (Ávila *et al*., 2009; SIAP, 2020). In this region, the State of Mexico stands out for its importance, since around 500 000 ha are cultivated with corn annually, with a mean state yield of 4289 kg ha^{-1}, and a production volume of two million tons (SIAP, 2020). Regardless, with the application technological recommendations and a wider use of improved varieties among producers, the corn yield could be increased from 4.2 to 6.0 Mg ha^{-1} (Tadeo-Robledo *et al*., 2014, 2016, 2017; Virgen-Vargas *et al*., 2016).

One of the most important supplies in agricultural production is the use of improved seeds. In this sense, one alternative to facilitate seed production and to raise the degree of adoption of hybrids corn seeds in the High Valleys is the use of types and sources of male sterility (genetic-cytoplasmic); this eliminates the hand detasseling or emasculation labor (Martínez-Lázaro *et al*., 2005; Tadeo-Robledo *et al.*, 2016). These genetic methods offer advantages in corn production and constitute an alternative for easy management in seed production (Sierra *et al*., 2016).

The National Institute of Forest, Agriculture, and Livestock Research (INIFAP) and the National Autonomous University of Mexico (UNAM) have developed the corn hybrids: H-51 AE, H-47 AE, H-49 AE, and H-53 AE (Espinosa *et al*., 2008, 2012, 2018), in which the male sterility scheme was used in the parents to facilitate seed production and promote the upkeep of the genetic quality (Tadeo-Robledo *et al.*, 2014, 2016). Corn hybrids have been well documented to respond differently to high plant densities with standard fertilization doses (Njoka *et al*., 2004; De la Cruz-Lázaro *et al*., 2009; Xu *et al*., 2017; Soleymani, 2018; Wang *et al*., 2019). In the United States of America, the country with the highest corn production in the world, plant density varies from 82 230 to 92 100 plants ha^{-1} (Xu *et al*., 2017). Contrastingly, plant density is complicated in corn producing regions in Mexico, where density varies from 20 000 to 42 000 plants ha^{-1}, for native varieties and from 65 500 to 83 333 plants ha^{-1} for other varieties improved and hybrids (Tinoco *et al*., 2008; van der Wal *et al*., 2006).

Population density is one of the factors that producers frequently modify to increase grain yield, although they do not always establish the correct density (De la Cruz-Lázaro *et al*., 2009). As the number of plants increases, the crops increase competition for light, water, and nutrients, which causes a decrease in root volume, number of ears, grain quantity and quality per plant, and reduces stalk diameter, favoring corn flopping (Vega *et al*., 2000; Maya and Ramírez, 2002; Sharifi *et al*., 2014). Ziegler *et al*. (1994) reported that grain yield increased when increasing plant density from 54 000 to 94 000 plants ha^{-1}, but decreased when reaching 97 000 plants ha^{-1}. Because of this, the objectives of the present study were: (1) to define the yield of six commercial corn hybrids released for the High Valleys of Mexico by the INIFAP and UNAM, established under three population densities in two environments of the State of Mexico, and (2) to determine the hybrid with the highest grain yield in two study areas and then define the adequate population density to recommend farmers.

MATERIALS AND METHODS

Study Site

The experiments were carried out in two different ecological niches during the spring-summer season of 2015 in the State of Mexico: School of Higher Studies Cuautitlán, UNAM (Experimental Field no. 7, 19° 41' NL, 99° 11' WL, 2274 masl) and Santa Lucía de Prias, Texcoco (Experimental Field of the Valley of Mexico, 19° 27' NL, 98° 51' WL, 2240 masl). In the latter environment, two experiments were established at different sowing dates.

Genetic Material

Six commercial white-grain corn hybrids adapted to the Haigh Valleys of Mexico were used: H-51 AE, H-53 AE, H-47 AE, H-49 AE, H-48, and Tsíri PUMA, developed by the INIFAP in collaboration with the UNAM.

Experimental Design

Each of the six hybrids was combined with three population densities: 50 000, 65 000, and 80 000 plants ha^{-1}. The experiment was established under a completely randomized block design with four replicates, with a total of 72 experimental units. Each experimental unit consisted of a row, five meters long × 0.8 m wide.

Experiment Development

Sowing was done on June 5th and 26th, 2015 in rows of 5 m long by 0.8 m wide. Two or three seeds were sown in each hole to ensure good plant density. The population density adjustment was done 45 days after sowing (das) as follows: (32 plants: 80 000 plants ha^{-1}), (26 plants; 65 000 plants ha^{-1}), and (20 plants; 50 000 plants ha^{-1}).

Harvest was done manually on December 10th and 14th of 2015, when the crops reached physiological maturity. All the ears were harvested and weighed for each experimental unit. Subsequently, 10 ears were selected to register the yield components. The evaluated variables were: plant height (cm), ear height (cm), male flowering (days), female flowering (days), ear cover (%), volumetric weight (kg hl^{-1}), weight of 200 grains (g), ear length (cm), ear diameter (cm), number of rows per ear, number of grains per ear, total number of grains per ear, grain percentage, and grain yield (kg ha^{-1}), calculated with the following formula: Yield = (TFW*DM*PG*CF)/8,600. Where: TFW= total field weight harvested in the experimental unit, DM = percentage of dry matter of a grain sample from five ears, PG= grain percentage estimated from five ears, CF= conversion factor to obtain grain yield per hectare, the quotient of dividing 10 000 m^2 by the useful plot in m^2, and 8600 = is a constant to estimate grain yield at a commercial humidity of 14% (Tadeo-Robledo *et al*., 2014).

Statistical Analysis

Analyses of variance and multiple means comparisons (Tukey HSD, $P \leq 0.05$), were done for all variables. The mean values were considered significantly different when $P \leq 0.05$. The statistical analyses were done with the SAT/STAT® ver. 9.0 software (SAS, 2002).

RESULTS AND DISCUSSION

Climatic Parameters in the Evaluation Sites

The climatic variables were registered during the development of the experiment. The total accumulated rainfall in the FESC-UNAM was 669.6 mm, while minimum and maximum temperatures fluctuated from 9.2 to 22.8 ºC, respectively. For CEVAMEX, the total accumulated rainfall was 465.8 and the minimum and maximum temperatures varied from 9.9 to 25.1 ºC, respectively (Figure 1). According to Kiniry and Bonhomme (1991), temperatures above 40 ºC during the flowering period can affect pollen grain emission, which directly affects crop productivity. Furthermore, temperatures below 8 ºC affect crop growth and development (Martínez, 2015).

Combined Analysis

The combined analyses of variance indicated significant ($P \leq 0.05$) effects in the genotype (G) and environmental (E) variation sources for all the evaluated variables, with the exception of ear length. These results indicate that the hybrids presented differential responses in the environments and the evaluated variables were influenced by effect of the environment. The population density (D) factor produced no differential response ($P \geq 0.05$) in any variable. In the interactions, no differences ($P \geq 0.05$) were registered with the exception of the ExG interaction on the grain yield variable (Table 1). The variation coefficients for the evaluated variables were in the order from 2.1 to 25.1%.

Table 2, shows the significant groups that define the contrasting responses of the hybrids in the evaluation environments. The higher mean yield corresponded to the first sowing date in CEVAMEX with 5497 kg ha^{-1} grain, and a difference of 765 kg ha^{-1} in relation to FESC-UNAM which had a lower yield (4732 kg ha^{-1}), both experiments were established on June 5th, 2015. The second sowing date (June 26th, 2015) affected the productivity of the evaluated hybrids in CEVAMEX, this was mainly due to the distribution of the rainfall which was concentrated in the first three months after sowing (Figure 1). To this regard Aguilar *et al*. (2015), mention that the water requirements of the crop are approximately 550 to 575 mm. It is important to point out that even though the environment in CEVAMEX was below the water requirements, it was the better environment for the performance of the hybrids in the first sowing date, compared with FESC-UNAM (Table 2).

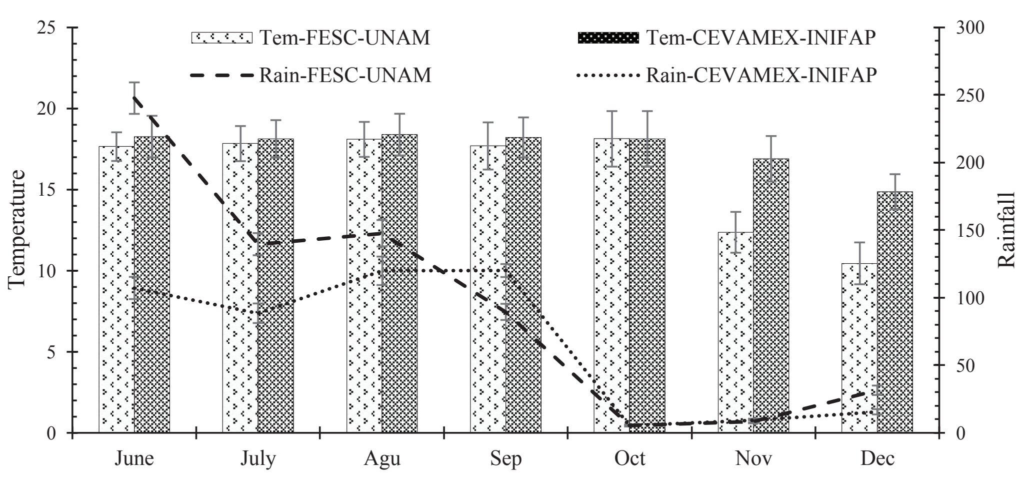

Figure 1. Mean temperature and rainfall registered during the development of the crop (June-December) in FESC-UNAM and CEVAMEX. Spring-Summer, 2015.

Table 1. Mean squares and statistical significance for different traits evaluated in six corn hybrids released by INIFAP and UNAM, considering three different population densities and three evaluation environments, FESC-UNAM and CEVAMEX. Spring-summer season, 2015.

Source of variation	Grain yield	Plant height	Plant ear	Male flowering	Female flowering	Volumetric weight	Weight 200 grains	Ear length	Grain percentage
	kg ha^{-1}	- - - - cm - - - - -		- - - - days - - - -		g hL^{-1}		cm	%
Environments (E)	21172913.6 **	130291.8**	23375.0**	2373.4**	3408.2**	20311.6**	2198.2**	24.2**	2290.4**
Genotype (G)	27688183.9 **	1981.0**	1564.7**	101.5**	91.0**	24962.7**	442.6**	3.9	8040.9**
Density (D)	NS	NS	NS	NS	NS	NS	NS	NS	NS
E × G	4659638.3 **	NS	NS	NS	NS	NS	NS	NS	NS
E × D	NS	NS	NS	NS	NS	NS	NS	NS	NS
G × D	NS	NS	NS	NS	NS	NS	NS	NS	NS
E × G × D	NS	NS	NS	NS	NS	NS	NS	NS	NS
CV (%)	NS	NS	NS	NS	NS	NS	NS	NS	NS
Mean	4893	222.7	98.7	81.4	83.2	743.1	54.9	14.3	468.9

* Significant 0.05; ** significant 0.01; CV = coefficient of variation.

In the evaluation of corn genotypes, it is important to consider, besides grain yield, the precocity of the materials. Through the three environments, male and female flowering days oscillated from 78 to 88 and from 79 to 91 days, respectively. The greatest precocity was in the CEVAMEX environment for both sowing dates (Table 2). Similar results are reported by Arellano *et al*. (2013), in a group of synthetic varieties and corn hybrids for Tlaxcala state. Moreover, CEVAMEX (in two sowing date) showed greater plant and ear height.

Table 2. Comparison of means of three test environments for the different traits evaluated considering the average of six corn hybrids and three environments of the High Valleys. FESC-UNAM and CEVAMEX. Spring-summer season, 2015.

Traits	CEVAMEX	FESC-UNAM	CEVAMEX	HSD (0.05)
	First sowing date		Second sowing date	
	- - - - June 5th. 2015 - - - -		June 26th. 2015	
Grain yield	5497 a[†]	4732 b	4449 b	485.1
Plant height (cm)	247 a	174 b	247 a	5.1
Plant ear (cm)	109 a	78 b	109 a	3.8
Male flowering (days)	78 b	88 a	78 b	0.7
Female flowering (days)	79 b	91 a	79 b	0.8
Volumetric Weight ((g hL^{-1})	752 a	754 a	724 b	8.2
Ear coverage	8.7 a	8.2 b	7.4 c	0.3
Weight 200 grains	55.6 b	60.1 a	49.1 c	2.7
Ear length (cm)	15.0 a	14.1 b	13.9 b	0.5
Ear row grains	15.1 a	15.6 a	15.5 a	0.5
Row grains	31.3 a	30.3 a	39.1 a	18
Ear diameter (cm)	4.5 a	4.5 a	4.3 b	0.1
Ear grains	472 a	472 a	462 a	24
Grain percentage (%)	85.7 b	86.5 a	84.5 c	0.6

[†] Different letters in the same row indicated different differences, according to the Tukey test ($P \leq 0.05$); HSD = honest significant difference; CEVAMEX = Valley of México Experimental Station; FESC-UNAM = Faculty of Superior Studies-Cuautitlán.

Reynoso *et al*. (2014) reported similar values in plant and ear height in a group of 17 hybrids evaluated in different environments in the High Valleys.

With regard to the yield components, differences were identified in the following variables: volumetric weight, weight of 200 grains, ear length, ear diameter, and grain percentage, but not in number of rows per ear, number of grains per row, and total number of grains per ear (Table 2). Of these variables, hectoliter weight stands out with a mean of 754 g hL^{-1} for the FESC-UNAM environment. It is worth mentioning that this parameter is a value that reflects grain health and the starch ratio in the kernel. These values are ideal for the Nixtamalized Flour Industry and the Corn Dough and Tortilla Industry (Salinas *et al*., 2010; Vázquez *et al*., 2015).

Agronomic Performance Among Genotypes

Table 3, shows the means comparison of the hybrids considering the three test sites. The high-yield hybrids were Tsíri-PUMA, H-49 AE, and H-53, with 5856, 5572 and 5569 kg ha^{-1}, respectively. Hybrid H-47 had the lowest grain yield with 3773 kg ha^{-1}. Similar results were reported by Martínez-Gutiérrez *et al*. (2018), in this same group of corn hybrids established in five sites in the High Valleys of the State of Mexico. Although the mean grain yield in this group was 11.2 Mg ha^{-1}, this is justified because in the evaluated sites, good agroclimatic conditions predominated, as well as deep soil types, optimum sowing dates, and mainly due to the characteristics of the materials, which are genetically different. Moreover, these hybrids were generated by the INIFAP and UNAM under a scheme of male sterility (AE), where there is coincidence in one or two lines that make up its genetic structure as hybrids (Espinosa *et al*., 2009; Tadeo-Robledo *et al*., 2014, 2016).

The Tsíri PUMA hybrid had the greatest precocity with 78 and 80 days to flowering. However, all the evaluated genotypes had a precocity under 90 days to flowering, which is desirable in production systems with water deficiencies or erratic distributions (Figure 1). According to some authors, precocious

Table 3. Comparison of means between six different corn hybrids, considering the average of three environments and three different population densities for the different traits evaluated. FESC-UNAM and CEVAMEX. Spring-summer season, 2015.

Traits	TSÍRI PUMA	H-49	H-53	H-51	H-48	H-47	HSD
		AE	AE	AE		AE	-0.05
Grain yield (kg ha^{-1})	5856 a[†]	5572 a	5569 a	4406 b	4179 b	3773 b	836.6
Male flowering (days)	78 c	83 a	82.7 a	82.3 a	80.7 b	81.8 ab	1.2
Female flowering (days)	80 c	84 a	84.5 a	83.9 a	82.4 b	83.9 a	1.4
Plant height (cm)	230 ab	218 cd	212.8 d	232.2 a	220.3 cd	222.8 bc	8.8
Ear height (cm)	96 bc	92 c	93.4 bc	110.6 a	99.4 b	99.9 b	6.6
Volumetric Weight (g hL^{-1})	775 a	765 ab	759.4 b	713.3 c	723.9 c	721.9 c	14.1
Ear coverage	8 a	8 a	8.7 a	7.7 bc	8.2 ab	7.4 c	0.6
Weight 200 grains (g)	60 a	55 ab	58.3 a	51.9 b	51.8 b	52.5 b	4.7
Ear length (cm)	14 a	15 a	14.6 a	14.6 a	13.8 a	14.1 a	0.9
Ear row grains	15 b	15 b	15.3 ab	15.9 a	15.9 a	15.4 ab	0.9
Row grains	31 a	31 a	30.9 a	30.6 a	30.1 a	47.9 a	31.1
Ear diameter (cm)	5 a	4 b	4.5 a	4.5 a	4.4	4.5 a	0.1
Ear grains	455 a	464 a	472.7 a	488.8 a	481.7 a	450.8 a	41.6
Grain percentage (%)	86 ab	86 ab	85.7 ab	84.9 b	86.1 a	84.8 b	1.1

[†] Different letters present significant differences between treatments in the different variables according to the Tukey test ($P \leq 0.05$); HSD = honest significant difference.

varieties are generally able to avoid the water deficient periods that appear with little rainfall (De la Cruz-Lázaro *et al*., 2009; Ángeles-Gaspar *et al*., 2010); this probably allowed this group of outstanding hybrids to have better rain water use in the first months (Figure 1). Plant height in the evaluated hybrids varied from 212.8 to 232.2 cm, and ear height ranged from 92 to 110.6 cm, respectively; these values, are within those reported by Tadeo-Robledo *et al*. (2014, 2015). There were no high percentages of bad covering in the evaluated hybrids, which avoided damage from birds and passage of humidity, considerably decreasing damages from ear rot.

We proved that the Tsíri PUMA hybrid showed the best results in grain variables like volumetric weight, weight of 200 grains, ear length, ear width, number of rows per ear, number of grains per row, total number of grains per ear, and grain percentage, respectively (Table 3). These results outperform data reported by Espinosa *et al*. (2010) for hybrid H-49 in their male-sterile and fertile versions in the High Valleys of Mexico.

Population Density

Given that the plant density factor had no significant effect on the evaluated variables in any of the three test sites, the optimum population density was not determined in the present study (Table 4). Thus, we can infer that the evaluated hybrids can endure high plant densities (Xu *et al*., 2017). These results agree with some works reported by Cervantes *et al*. (2014). We suggest carrying out a wider exploration of population densities in future works with the three best performing hybrids.

Population density is one of the factors that producers frequently modify to increase grain yield, although they do not always establish the adequate density, since with a greater number of plants, competition for light, water, and nutrients increases.

Table 4. Comparison of means between population densities for the different traits evaluated in the mean of six corn hybrids of INIFAP and the UNAM of High Valleys evaluated in the FESC-UNAM and CEVAMEX. Spring-summer season, 2015.

Traits	Plant densities (plants ha^{-1})			
	65 000	50 000	80 000	HSD (0.05)
Grain yield (kg ha^{-1})	4964 a†	4871 a	4843 a	485
Male flowering (days)	81 a	81 a	81 a	0.7
Female flowering (days)	83 a	83 a	83 a	0.8
Plant height (cm)	223 a	221 a	224 a	5.1
Ear height (cm)	98 a	99 a	99 a	3.8
Volumetric weight (g hL^{-1})	740 a	744 a	745 a	8.2
Ear coverage	8.0 a	8.1 a	8.2 a	0.3
Weight 200 grains (g)	54.0 a	54.1 a	56.7 a	2.7
Ear length (cm)	14.2 a	14.3 a	14.5 a	0.5
Ear row grains	15.3 a	15.5 a	15.4 a	0.5
Grains row	30.1 a	39.7 a	30.8 a	18
Ear diameter (cm)	4.4 a	4.5 a	4.4 a	0.1
Ear grains	459 a	473.5 a	473.3 a	24.1
Grain percentage (%)	85.6 a	85.4 a	85.6 a	0.6

† Different letters present significant differences between treatments in the different variables according to the Tukey test ($P \leq 0.05$); HSD = honest significant difference.

CONCLUSIONS

The best evaluation sites were those established at the beginning of the rainy season, as is the case of CEVAMEX (June 5th, 2015). In this environment, the Tsíri PUMA, H-49 AE, and H-53 AE hybrids showed the best agronomic performance and grain characteristics. Furthermore, no differences were observed from changes in plant densities, concluding that plant density is not a factor that influences grain yield in the hybrids in this study. Therefore, we recommend using the second population density, 65 000 plants ha^{-1} so farmers can avoid spending in greater amounts of seeds to obtain the same yields. If a density of 50 000 plants ha^{-1} is used, too much space is wasted and there could be problems with regard to population. Contrastingly, a higher population density increases costs as more seeds are needed to establish greater population densities.

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